INTERNATIONAL JOURNAL OF CLIMATOLOGY

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Journal:	*International Journal of Climatology*
Manuscript ID	JOC-17-0557.R2
Wiley - Manuscript type:	Research Article
Date Submitted by the Author:	n/a
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Keywords:	jet stream, North Atlantic Oscillation, precipitation, seasonal forecasting, temperature, correlation, EOF, UK regional climate
Country Keywords:	United Kingdom Of Great Britain And Northern Ireland

North Atlantic circulation indices: links with summer and winter UK temperature and precipitation and implications for seasonal forecasting.

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Running head:

North Atlantic atmospheric circulation and UK climate.

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Abstract

UK seasonal mean temperature and precipitation conditions are extremely variable from one year to the next but in the last decade have featured several cool, wet summers and mild, wet winters interspersed with some notable cold winter episodes. Jet stream variability is a major determinant of these fluctuations, and is often represented by the North Atlantic Oscillation (NAO) index. Recent work has shown some evidence of promising predictability in the winter NAO from one to two months ahead, while summer predictability remains very limited. Although the phase and magnitude of the NAO influences total UK rainfall, there are regional variations which it does not explain. Here we examine the relationship between UK regional summer and winter precipitation and temperature and a range of North Atlantic atmospheric circulation indices. While the NAO shows a significant relationship with temperature in both seasons and summer rainfall over most of the UK, the picture in winter is more complicated with other circulation indices such as the East Atlantic pattern explaining rainfall anomalies in southern England. Other indices also show significant relationships with precipitation in regions where the NAO does not. Since UK weather is determined by the interplay between different circulation indices, attention should be given to developing seasonal forecasts of other circulation indices to complement the NAO forecasts. We also find that some potential drivers of jet stream variability are significantly associated with UK temperature and rainfall variability, particularly in summer. This provides further scope for producing seasonal forecasts based directly on these drivers. Improved seasonal forecasts will be useful to a range of end users in agriculture, energy supply, transport and insurance industries and can be extended to other UK weather variables such as extreme rainfall events and storm frequency, and related metrics such as wind power capacity and solar energy.

Key words: correlation**,** EOF, jet stream, North Atlantic Oscillation, precipitation, seasonal forecasting, temperature, UK regional climate

1. Introduction

UK weather is extremely variable on intraseasonal and interannual timescales, with changes in storminess, wind speeds, rainfall and temperature associated with the variability of the North Atlantic jet stream (e.g. Hulme and Barrow, 1997; Woollings, 2010). Jet stream and associated storm track variability can be represented by the North Atlantic Oscillation (NAO) index (e.g. Vallis and Gerber, 2008; Hanna and Cropper, 2017) and there are strong correlations between jet latitude and the NAO (e.g. Woollings and Blackburn, 2012). The NAO can be defined in several ways, but is often represented as the normalised sea-level pressure (SLP) difference between the Azores, Lisbon or Gibraltar and Iceland (e.g. Hurrell, 1995, Jones et al., 1997; Cropper et al., 2015). An increased (decreased, or even reversed) pressure difference results in a positive (negative) NAO phase, the pressure gradient being proportional to the strength of the geostrophic westerlies. The location of the NAO nodes varies over the seasons, and between positive and negative NAO phases (Wanner et al, 2001) and this variability can be better captured by an empirical orthogonal function (EOF) approach to identifying the NAO (e.g. Hurrell et al., 2003), with the associated principal component (PC) time series representing the NAO index. Correlation between the Hurrell station-based and PC-based winter (December-February; DJF) NAO indices is 0.88 from 1899-2016 whereas for the same period in summer the correlation is only 0.59; this reflects the shift in location of the summer centres of action, which is better captured by using EOFs. A summer NAO index (SNAO) has been proposed, partly to reflect this seasonal difference (Folland et al., 2009). As the NAO is equivalent barotropic in nature, it can also be derived from 500hPa geopotential height fields and the NOAA Climate Prediction Center (CPC) construct an NAO index based on the rotated EOF of 500hPa geopotential height anomalies. The NAO can also be identified by one-point correlation maps and cluster analysis, as described by Hurrell and Deser (2009).

In winter, a positive NAO is associated with mild, wet winters in the UK and western Europe, with increased frequencies of stronger westerly winds in the mid-latitudes (Hurrell and Deser, 2010; Burningham and French, 2013) and a positive correlation between temperature and NAO phase over the UK and northern Europe (Comas-Bru and McDermott, 2014). Generally there is a north-eastward shift of storm activity, with more storms in northern Europe (Hurrell and Deser, 2009). A more negative NAO generally brings colder, drier conditions to northern Europe. In summer however, there is a poleward shift in the jet stream and the NAO nodes. Consequently a positive summer NAO tends to be associated with warm dry summers in northwestern Europe, low-pressure systems being steered to the north of the British Isles, whereas a negative NAO in summer preferentially directs rain-bearing low-pressure systems over the region (Folland et al., 2009; Dong et al., 2013a).

The NAO is the first EOF of SLP over the North Atlantic region. The percentage of variance explained is domain- and time-period dependent, but is greater in winter than in summer and can be typically up to 40% of total variance (e.g. Hurrell, 1995). However, a significant amount of SLP variance is explained by other lower-order EOFs. The second mode of variability is the East Atlantic (EA) pattern (e.g. Barnston and Livezey, 1987; Moore and Renfrew 2012), which in its positive phase is represented by a low-pressure monopole to the west of Ireland. An EA index with reversed polarity has been used in a number of papers (e.g. Wallace and Gutzler, 1981; Comas-Bru and McDermott, 2014; Zubiate et al., 2016), but this does not affect the relationships identified, just the polarity. The third EOF, the Scandinavian pattern (SCA), features high pressure over Scandinavia in its positive phase (e.g. Barnston and Livezey, 1987). As with the NAO, the CPC version of these EOFs (EA-CPC and SCA-CPC) are derived from 500hPa GPH anomalies. The interplay between these modes of atmospheric circulation variability can more fully describe North Atlantic jet stream variability (Woollings and Blackburn, 2012). The percentage of variance explained by these two additional EOFs depends on the time period, domain and atmospheric variable under consideration, but can be up to 25% for the EA (e.g. Woollings and Blackburn, 2012) and around 10% for SCA.

There has been considerable debate over the extent to which the NAO is purely a mode of atmospheric internal variability, or whether it is driven by external factors. In numerical experiments James and James (1989) found that a mode similar to the NAO can be internally generated, and Feldstein (2000) identified the interannual variability of the winter NAO as arising primarily from unforced climate noise. However the orography of the Rocky Mountains together with the land-sea temperature contrast off the eastern coast of North America, exert an influence on the North Atlantic storm track pattern (Vallis and Gerber, 2008; Brayshaw et al., 2009) which in turn impacts upon the NAO phase. Indeed, the NAO changes could be regarded as the variability of the storm track (Vallis and Gerber, 2008).

Despite the NAO being a mode of internal variability, there has been recent significant progress in seasonal forecasting of the winter NAO from one to two months ahead, using dynamical forecasting models (Scaife et al., 2014; Stockdale et al.,2015). This is a consequence of the influence of slowly varying boundary conditions such as North Atlantic and Pacific sea-surface temperatures (SST) and Arctic sea-ice variability, which influence the atmospheric circulation over longer timescales (e.g. Hall et al., 2015; Smith et al., 2016), with the possibility that forecasts can be extended to over a year ahead (Dunstone et al., 2016). Recent statistical forecasts of the winter NAO provide further evidence for this link (Hall et al., 2017a; Wang et al., 2017). A reliable seasonal forecast of the winter NAO will indicate the weather patterns expected in the UK during the upcoming winter months, which is invaluable to planners and decision makers. Several studies demonstrate the potential applications of these forecasts in important areas such as hydrological event prediction (Bell et al., 2017), wind and solar energy supply and energy demand (Ely et al., 2013; Clark et al., 2017) and transport networks (Palin et al., 2016). For example, for a winter forecast of a negative NAO, cold calm weather conditions would be expected together with increased energy demand, yet supply from wind energy will be reduced; a positive NAO forecast would be associated with the probability of increased rainfall and flood risk in certain areas.

Seasonal forecasts often focus on the NAO and ignore the contribution of the other circulation indices to temperature and rainfall anomalies, and moreover do not distinguish between UK regional variations, limiting the usefulness of the forecast. There is a significant positive correlation between overall UK winter precipitation and the winter NAO (e.g. Svensson et al., 2015), as a consequence of the shift in storm tracks. However, on a regional basis this is potentially misleading as the heavier precipitation over the north and west, due to orography, frontal rainfall and to geographical location, skews the overall picture (e.g. Comas-Bru and McDermott, 2014). Figure 1 shows rainfall anomaly maps for three recent positive NAO winters. The distributions of rainfall anomalies are very different, and the generalised positive relationship between NAO strength and UK rainfall is not clear. The rainfall anomaly pattern is not a straightforward function of NAO strength as winter 2014-15 has the largest NAO value, yet positive precipitation anomalies are lower and reduced in extent, while areas with negative anomalies increase. In 2015-16, with an intermediate positive NAO value, the largest rainfall anomalies are over the northern UK and 2013-14 has the largest rainfall anomalies over the south of the UK, as well as southern and central Scotland, although the NAO value is the lowest. These positive rainfall anomalies over southern England in 2013-14 have been attributed to the NAO (e.g. Huntingford et al., 2014). However, van Oldenborgh et al. (2015) point out that the winter NAO is significantly correlated with rainfall only in the north and west of the UK, and the NAO does not explain rainfall variance in the south. A straightforward NAO forecast for each of these winters, even if accurate, would not predict the observed regional distribution of rainfall anomalies, or indeed their magnitude, based on a linear relationship. Comas-Bru and McDermott (2014) illustrate the effect of the interplay between the NAO and EA on winter precipitation patterns (their Figure 9), indicating that the EA phase plays an important role in determining regional variability of precipitation anomalies under positive NAO conditions. Figure 2 shows SLP and zonal wind differences between 2013-14 and 2014-15. The North Atlantic jet is stronger in the former, and displaced southward, despite the lower NAO value. In figure 2b, a clear EA pattern emerges, indicating a more positive EA in 2013-14. There is also a contribution from the positive SCA pattern in 2013-14 relative to 2014-15. Therefore it is evident that the regional rainfall anomalies of a particular season cannot be attributed solely to the NAO.

At present there is little skill in forecasts for the summer North Atlantic atmospheric circulation, yet such skill would be of particular benefit to the agricultural and leisure sectors. However, a recent study has identified some possible sources of predictability (Hall et al., 2017b). Decreased (increased) sea-ice extent in the Barents-Kara Sea is associated with a southward (northward) displacement of the jet in the following summer, which may be related to the persistence of sea-ice thickness anomalies through the winter (Blanchard-Wrigglesworth et al., 2011). The recent cool wet UK summers (e.g. Blackburn et al., 2008; Dong et al., 2013b) have also been associated with the positive phase of the Atlantic Multidecadal Oscillation (AMO) of Atlantic-wide SST anomalies (e.g. Sutton and Dong, 2012).

In this study we explore the relationships between a number of North Atlantic atmospheric circulation indices and temperature and rainfall over the UK, for both summer (JJA) and winter (DJF), in order to inform the future development of seasonal forecasts that are tailored to specific regions of the UK. We also identify some potential links between identified drivers of jet stream variability and precipitation and temperature over the UK, which may further enhance seasonal forecasting potential. Section 2 describes the data used, methods are outlined in section 3 and results presented in section 4. Section 5 contains a wider discussion of the results and a summary follows in section 6.

2. Data.

A summary of datasets, time periods and regions extracted is given in Table 1. Gridded rainfall and temperature data for the UK are available at 5km resolution (UKCP09; Perry and Hollis 2005). These are based on observations and use regression to fill gaps in station data and inverse-distance weighted interpolation of regression residuals to generate values on a regular grid, considering factors such as latitude, longitude, altitude, coastal and urban influences. In addition, regional rainfall and temperature records for the UK are available from the Met Office. A time series of monthly precipitation for UK regions (HadUKP; Alexander and Jones, 2001) is also used. These regions (Figure S1) are based on areas of coherent precipitation variability (Wigley et al., 1984). The Central England Temperature index (CET; Manley, 1953; Parker et al., 1992) and regional HadUKP data are used for comparison with UKCP09 gridded data in order to identify associations with atmospheric circulation indices.

The NAO, EA and SCA indices are available from the CPC. These are time series derived from the rotated EOFs of 500hPa GPH anomalies, based on the NCEP/NCAR reanalysis (Kalnay et al., 1996) over the whole of the Northern hemisphere (http://www.cpc.ncep.noaa.gov/data/teledoc/ea.shtml). The summer NAO (SNAO) is the first EOF of SLP over 40-70N, 90W-30E, using NCEP/NCAR data, and is available from Climate Explorer (www.climexp.knmi.nl). In addition, the first three EOFs of North Atlantic SLP and their principal component (PC) time series are calculated for summer and winter over 1951-2014 using 20CRv2c SLP data (Compo et al., 2011) and for 1979-2016 using ERA-Interim (ERA-I) reanalysis data (Dee et al., 2011). Separate EOFs are calculated for 1979-2014 (1980-2014 for DJF) from both 20CRv2c and ERA-I to allow a direct comparison between EOFs from different reanalyses for the same time period. The area used is 20-80N, 90W-40E which is identical to the area used for the Hurrell PC NAO index; new indices are calculated to ensure that the first three EOFs are available and orthogonal. SLP is chosen since 20CRv2c uses SLP observations as a boundary condition and therefore SLP data are likely to be more accurate than 500hPa GPH. Finally, the Hurrell station-based NAO index is used as an example of a station-based index and is described in the NCAR/UCAR Climate Data Guide (www.climatedataguide.ucar.edu).

Metrics of jet speed and latitude variability are derived according to Woollings et al. (2010). Daily zonal wind speeds over 700-900hPa from the North Atlantic region (16-76°N, 60-0°W) are averaged vertically and a zonal-mean wind speed is calculated for each 2° latitude band. The maximum zonal mean gives the speed of the jet for each day, while the jet latitude is given by the latitude at which this maximum occurs. The daily time series of jet speed and latitude are filtered using a 61-point Lanczos filter to remove synoptic-scale variability (Duchon, 1979) and seasonal values of jet speed and latitude are calculated. Jet latitude and speed time series use ERA-I for 1979-2016 (JJA), 1980-2016 for DJF, and a longer time series uses 20CRv2c for 1951-2014. The ensemble mean values are used from 20CRv2c, as post-1950 the ensemble spread is much reduced, and are in close agreement with jet metrics from other reanalysis products (e.g. Woollings et al., 2014). 850hPa vector winds and 925hPa air temperature anomalies are obtained from NCEP/NCAR reanalysis (Kalnay et al., 1996) for 1951-2016 and are used in composites of high and low circulation index years, to identify atmospheric features associated with the indices.

To identify any associations between drivers of jet variability and UK rainfall and temperature, datasets of key drivers are used as identified by Hall (2016) for winter and Hall et al. (2017b) for summer. Both use multiple regression, composite and wavelet coherence analysis to determine potential drivers of jet speed and latitude. Hall (2016) identifies January AMO and Atlantic and Pacific tropical precipitation as drivers of winter jet speed. Drivers of winter jet latitude include the October N3.4 index, November sea-ice concentration in the Barents-Kara Seas, October Eurasian snowcover and the autumn Quasi-biennial oscillation (QBO). Sea-ice concentration is obtained for the Greenland Sea (GI) and Barents-Kara Sea regions (BKI), from the HadISST1 dataset (Rayner et al., 2003). Snowcover data from Eurasia and North America are obtained from Rutgers University Snow Lab Robinson et al., 2012; http://climate.rutgers.edu/snowcover/). Two indices represent Atlantic SST: (1) AMO (Enfield et al., 2001) index data are obtained from the Earth System Research Laboratory (www.esrl.noaa.gov/psd/data/timeseries/AMO) based on the Kaplan SST dataset (Kaplan et al., 1998, updated); (2) A North Atlantic tripole index uses the methodology of Czaja and Marshall (2001), based on the HadISST1 SST anomaly taken over 60-40°W,40-55°N, minus the anomaly over a southern region 80-60°W, 25-35°N. Anomalies are relative to the 1981-2010 climatology. Monthly sunspot numbers are obtained from the Solar Influences Data Analysis Center (http://sidc.oma.be/). The QBO data are obtained from the Free University of Berlin (www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/; Naujokat, (1986), updated). Tropical central Pacific SST anomalies are represented by a discontinuous El-Nino 3.4 index (N3.4) as described in Folland et al. (2012), derived from HadISST1 data. Tropical Atlantic precipitation anomalies from the Global Precipitation Climatology Project (GPCP v2; Adler et al., 2003) are also used. All these drivers are taken from 1951-2016, with the exceptions of snow cover and tropical precipitation, which are available from 1979. Figure S2 shows these regions.

All datasets are linearly detrended to isolate the interannual association between circulation indices and temperature and rainfall. Winters are labelled by the year of the January, following standard meteorological convention.

3. Methods

In order to identify the dominant North Atlantic atmospheric circulation patterns that influence UK weather on a seasonal scale, EOFs of North Atlantic SLP are constructed using latitude weightings (multiplying by the square root of the cosine of latitude). The significance of the separation of the EOFs is assessed using North's Rule of Thumb (North et al., 1982). For winter and summer, the first three EOFs are found to be distinct. The EOF patterns also illustrate changes in circulation patterns between summer and winter. The principal components (PCs) are used as circulation indices for comparison with NAO-CPC, EA-CPC and SCA-CPC, as well as with metrics of jet speed and latitude.

A simple correlation analysis (Pearson's Product Moment) is conducted to identify relationships between the circulation indices themselves and associations between circulation metrics and UK temperature and rainfall. Significance is calculated based on effective degrees of freedom according to Bretherton et al. (1999), allowing for temporal autocorrelation in the time series. In addition, spatial autocorrelation and issues associated with multiple testing occur with correlation maps, which lead to areas of significance being too extensive due to overestimation of the number of spatial degrees of freedom. To minimise this effect the False Discovery Rate (FDR, Benjamini and Hochberg, 1995) is used. The *p*-values of the *N* tests are ordered. The smallest and nominally most significant of these tests is denoted $p_{(1)}$ and the largest and least significant is $p_{(N)}$. Individual tests are taken as significant if the corresponding *p*-value is no greater than:

$$p_{FDR} = \max_{j = 1, \dots, N} \left\{ p_j : p_j \leq \frac{j}{N} \alpha_{global} \right\} \qquad (1)$$

The sorted *p*-values are assessed on a sliding scale. If the largest, $p_{(N)}$ is no greater than α_{global} =FDR, all the tests are taken as being significant. The null hypothesis is rejected for the test having the largest p value satisfying equation 1, as are the null hypotheses for all tests with smaller *p*-values (Wilks, 2011; pp180-181).

Composites of vector wind and air temperature anomalies are obtained for the ten highest and lowest circulation index years from the detrended time series, to identify larger-scale atmospheric circulation features associated with the circulation indices and UK precipitation and temperature patterns, in order to explain particular patterns of precipitation and temperature correlation with circulation indices.

Correlation is also used to determine the strength and sign of association between identified drivers of North Atlantic jet stream variability and UK precipitation and temperature.

4. Results

4.1. EOF analysis of North Atlantic SLP

The EOFs derived from 20CRv2c for 1951-2014 are shown in Figure 3. Figures S3 and S4 show the equivalent for 20CRv2c and ERA-I, for 1980-2014 (DJF) and1979-2014 (JJA). For all periods, the first EOF is clearly recognisable as the NAO (SNAO in summer; Figures 3a,d; S3a,d; S4a,d). For the longer period, in summer EOF3 bears a closer resemblance to the EA than does EOF2 (Figure 3e,f), whereas in winter it is EOF2 that most closely resembles the EA, and EOF3 the SCA, although the high-pressure centre is displaced westwards compared to the classic SCA (Figure 3b,c). The wintertime EOF2/EA and EOF3/SCA agreement is evident in EOFs from both reanalyses from 1980 onwards, (Figure S3), although there is a suggestion that EOF3 for both reanalyses (Figure S3c,f) could be a better fit for the East Atlantic-West Russian pattern which is often identified as the fourth EOF of North Atlantic atmospheric pressure or GPH, characterised by a wavelike pattern extending from the south-west to north-east (e.g. Lim, 2015). In summer the picture is less clear-cut for the period from 1980, with EOF2 resembling a combination of EA and SCA in both reanalyses (Figure S4b,e), while the two EOF3s are very different (Figure S4c,f). It is actually EOF4 of ERA-I that most closely resembles EOF3 of 20CRv2c and SCA (not shown). This variation among the first three EOFs of SLP reflects a number of factors. First, different domains and time periods used for computing EOFs will introduce variations, particularly with the lower-order EOFs. There will also be differences between EOFs calculated using SLP and 500GPH. EOFs do not reflect change over time and are stationary, and therefore EOFs calculated for different time periods are likely to reflect differences in relative strength between the EOFs, and changes in intensity and location of centres of action. Further differences between the EA-CPC and SCA-CPC patterns and the EOFs and PCs calculated here are attributable to the former being calculated through rotated EOFs for the whole of the northern hemisphere. It is notable that while spatial patterns are similar for 20CRv2c and ERA-I EOFs (Figures S3, S4), the amplitude of the EOFs in ERA-I is much less. Using NCEP/NCAR reanalysis produces amplitudes similar to those for 20CRv2c (not shown), and the reasons for the ERA-I discrepancy are unclear at present.

4.2. Relationships between Atlantic Circulation Indices

The correlations between the circulation indices for 1951-2014 and 1979-2016 are shown in Table 2. There is good agreement between correlations over the two time periods; however, some discrepancies occur between PC2 and PC3, particularly in summer, reflecting the differences identified above between the EOF spatial patterns. For winter there is agreement between the identification of PC2 and PC3 over the two different time periods. In summer, by contrast, PC2 and PC3 are exchanged between the two time periods, as indicated by the EOF patterns in Figures 3 and S4. The EA-type pattern may have become more significant in the latter period in summer, promoting it to EOF/PC2. This switching of EOFs could be modulated by low-frequency SST variability such as the AMO. The latter has been in a positive phase since the mid-1990s and positive SST anomalies will be associated with lower SLP west of Ireland, corresponding to a positive EA. The summer EA has been largely positive since 2000.

In winter for the period 1951-2014, there is good agreement between the different NAO-like indices (NAO-CPC, PC1, Hstat, r=0.89-0.94) and jet latitude correlates highly with all three (0.77,0.82 and 0.79 respectively), indicating that the NAO-like circulation indices all capture more than 60% of the variance of winter jet latitude (R^2). EA-CPC correlates well with PC2 (0.82) and with both jet speed and latitude (0.53 and -0.57 respectively), in agreement with Woollings and Blackburn (2012). SCA-CPC shows a significant negative correlation with jet latitude (-0.29) while the correlation with jet speed is insignificant. The correlation between SCA-CPC and PC3 is 0.35, notably weaker than the correlation between PC2 and the EA-CPC; therefore PC3 from this analysis is similar but not equivalent to SCA-CPC. All leading modes of variability contribute to jet latitude variance (CPC: NAO 59.3%, EA:

33%, SCA: 8%; note here the variance total for the first three EOFs slightly exceeds 100% as rotated EOFs and their PCs are non-orthogonal).

In summer, from 1951-2014 the association between NAO-like indices is weaker. Correlation coefficients are between 0.81 and 0.90 for pattern-based EOF indices (NAO-CPC, PC1, SNAO) while those of the NAO-CPC, PC1 and SNAO with Hstat are 0.47, 0.53 and 0.27, reflecting the shift in the NAO nodes in summer, which is not well captured by the fixed-point station-based approach. PC1, NAO-CPC, SNAO and jet latitude are portraying essentially the same atmospheric circulation variability. The station-based index is not as strongly correlated with jet latitude (0.37) confirming the deficiency of this type of index in representing summer jet stream variability. As with winter, the EA-CPC shows a similar strength but opposite sign of correlation with jet speed and latitude.

PC2 represents a mix of EA and SCA while PC2 and PC3 are well correlated with summer jet speed (-0.53, 0.59) compared with 0.36 and -0.07 for EA-CPC and SCA-CPC. The correlations for 1979-2016 show general agreement with those for the longer period, although the exchange of PC2 and PC3 is evident in the correlations. Jet speed and latitude are not significantly correlated in either season, indicating that different factors may influence their variability (Woollings et al., 2010).

4.3. Relationships between North Atlantic circulation indices and UK regional temperature and precipitation

Correlations between the full range of atmospheric circulation indices and regional temperature and precipitation are presented in Table 3. Correlation maps based on circulation indices and temperature and precipitation from UKCP09 (Figures 4-7) illustrate the spatial patterns of correlations, which is particularly important for temperature as CET only covers central England and gives no indication of regional variations. Only one map is shown for indices relating to jet latitude variability (PC1); maps for similar indices such as jet latitude, NAO-CPC and SNAO show little qualitative difference to that shown here.

4.3.1 Temperature

Correlations of the indices of jet latitude (NAO-CPC, PC1, Hstat, SNAO) with CET are positive and significant in both seasons, with the exception of Hstat in summer (Table 3a,b). In winter, EA-CPC, SCA-CPC and PC3 show no significant correlation with CET, while PC2 has a positive correlation. In summer, EA-CPC has a significant negative correlation with CET, PC3 shows no significant relationship and PC2 is significantly positively correlated with CET although SCA-CPC is not.

In Figures 4 and 5, EA-CPC, SCA-CPC and PC3 have no significant correlations with winter temperature over the whole of the UK (Figure 4a,b,e). However, PC2 shows significant positive correlations in the southern half of the UK (Figure 4d); a similar pattern to that shown by the EA-CPC but with stronger correlations and similar to the correlation pattern for jet speed (Figure 4f), reflecting the strong correlation between jet speed and PC2 (0.73) in Table 2. PC1 has positive significant correlations with winter temperature over the whole of the UK (figure 4c), and these associations get stronger to the north and west.

While winter temperature correlations reveal a north-south variation (Figure 4), those in summer have a more meridionally-oriented variability (Figure 5). The EA-CPC has significant negative correlations with temperatures in the west of the UK (Figure 5a), while PC1 is positively correlated with temperature for all the UK except western Scotland, although correlations are less strong than in winter (Figure 5c). Correlations with SCA-CPC, PC3 and jet speed are insignificant. Interestingly, PC2 which has a correlation of 0.43 with SCA-CPC (Table 2), shows significant positive correlations with summer temperature over all but eastern East Anglia and the North Sea coast of Lincolnshire and Yorkshire (figure 5d).

4.3.2 Precipitation

In winter significant positive correlations occur for Scotland and Northern Ireland precipitation with jet latitude-related metrics (NAO-CPC, jet latitude, PC1,Hstat; Table 3a), while there are significant negative correlations with eastern and southern England precipitation, clearly seen on Figure 6c. For large parts of the Midlands, Wales and south-west England, the NAO has no significant correlation with precipitation as either a northward or southward shift in the jet will steer low pressure systems away from this region. The negative correlations on the eastern side of the UK are due to these regions lying in the rain shadow of the prevailing westerlies under a positive NAO, while for a negative NAO, anomalous easterly winds may bring moisture off the North Sea as precipitation along the east coast. PC2 and EA-CPC have significant positive correlations with precipitation across England and Wales, with correlations being stronger for PC2, significant correlations extending to western Scotland and northwest England and the whole of Northern Ireland (Figure 6a,d). SCA-CPC and PC3 show significant negative correlations with precipitation, mostly over the northern and western UK regions, which are stronger and more extensive for PC3 (Figure6b,e), significance for SCA-CPC being restricted to the northwest of Scotland. Jet speed has a similar correlation pattern to PC2 and EA-CPC, but with a more westerly focus, insignificant correlations stretching down the east coast of England (Figure 6f).

For summer, the indices that primarily represent jet latitude variability (NAO-CPC, latitude, PC1 and SNAO) show almost exclusively significant negative correlations with regional precipitation (Table3b, Figure 7c), regardless of region although only SNAO has a significant correlation in the north of Scotland. The summer EA-CPC more closely resembles PC3 and both have positive significant relationships with precipitation (Table 3b, Figure 7a,e), these being stronger and with more widespread significance for the EA-CPC, although this significance appears patchy in southeast England and the extreme north west of Scotland (Figure 7a). PC2 and SCA-CPC show negative correlations with rainfall, significant for both indices in Scotland and with some significance over north-west England, Wales and Northern Ireland for PC2 (Figure 7b,d). Jet speed has a significant positive correlation with precipitation in the west of Scotland, precisely where the PC1 correlations are insignificant (Table 3b, Figure 7f).

4.4. Explaining features of North Atlantic circulation-UK regional climate correlations.

Composites of vector wind and 925hPa air temperature anomalies (Figures 8 and 9) yield important features of the North Atlantic atmospheric circulation that explain the correlations discussed above. Figures show high minus low index years, indicating conditions under a positive circulation index.

4.4.1 UK Temperature

In winter, the positive correlations of EA-CPC/PC2/jet speed with temperature over south and central England (Figure 4a,d) are associated with south westerly wind anomalies advecting warmer air over the UK (Figure 8a-d,k,l) for the positive phase EA-CPC/PC2. For PC2 warm anomalies extend to North Africa and are slightly stronger over western Europe compared with EA-CPC (Figure 8b,d): hence the significant correlations with temperature in Figure 4d. In contrast, for SCA/PC3 anomalous easterly winds advect cold air from continental Europe over the UK, leading to lower temperatures (Figure 8e-h) and thw weak negative correlations with temperature (Figure 4b,e). SCA-CPC and PC3 are associated with anomalously low temperatures over central Asia (not shown), although the centre of this is shifted westwards for PC3 and temperatures are not as low (60°E, -4.0°C for PC3; 90°E, -6.4°C for SCA-CPC). Under positive NAO conditions (PC1), strong westerly wind anomalies advect relatively warm maritime air over the UK, and into northern Europe (Figure 8i,j).

While winter correlations with temperature change in a north-south direction, those in summer change from east to west, which is explained by summer changes in circulation patterns and the locations of regions of anomalous temperature (Figure 9). The EA-CPC (Figure 9a,b) and jet speed (Figure 9k,l) are negatively correlated with temperatures in the west of the UK, correlations being significant for the EA-CPC (Figure 5a). Both circulation patterns show a negative temperature anomaly over the central North Atlantic (positive EA, stronger jet), but the centre of this is located directly over the UK for the EA-CPC, exerting a stronger influence on UK temperatures than for jet speed (Figure 9b, c.f. 9l). For PC3, (Figure 9g,h) while the circulation pattern is similar to that of the EA-CPC, it is displaced westwards, the mid-Atlantic cold anomaly is further west and winds over the UK are south-westerly, with insignificant correlations between the circulation pattern and regional temperature anomalies (Figure 5e). Vector winds suggest the cold anomaly for EA-CPC originates with the southerly advection of cold air from Iceland and Greenland (Figure 9a), and in the case of jet speed, from the Baffin Bay region (figure 9k), whereas for PC3, there is evidence of mixing of cold Greenland air with air drawn up from the Gulf of Mexico, reducing the impact of the negative temperature anomaly (Figure 9g). The PC2/SCA-CPC patterns are associated with positive UK temperature anomalies (Figure 9d,f), with easterly wind anomalies bringing in warm continental air. The easterlies are stronger for PC2 and the warm continental anomaly extends further west over the UK. The lack of significant correlation between temperature and PC2 along the North Sea coast of England (Figure 5d) is likely to be due to local conditions, where Haar fog is frequently experienced as warm air flows over the cold North Sea, cooling areas along the coast and adjacent areas.

In the positive phase of PC1 (or SNAO), the southern UK lies under an anomalous easterly flow of warm continental air, leading to anomalously warm conditions, while north-west Scotland lies under the westerly jet (Figure 8i), advecting cooler air from the North Atlantic and weakening the correlation with temperature in this region (Figure 5c) .

4.4.2. UK Precipitation

The positive winter correlation between southern UK precipitation and the EA-CPC/PC2/jet speed is explained by the moisture-laden south-westerlies, with their main focus on the southern regions of the UK (Figure 8a,c,k). Conversely, for a positive phase of PC1, the jet stream lies over the northern half of Britain (Figure 8i), with heavier rainfall over western Scotland and north-west England, but with an east/west divide caused by the orographic impact on rainfall, and the rain-shadow effect (Figure 6c). The rainfall correlation pattern for

SCA-CPC/PC3 is almost the reverse of the PC1/NAO pattern (Figure 6b,e), with significant positive relationships along the east coast as easterly winds bring moisture from the North Sea, while the western regions are in the rain-shadow with respect to these easterlies. The effect may be more pronounced for the SCA-CPC relative to PC3 as the easterly winds are displaced northwards and have a longer fetch across the North Sea (Figure 8e,g).

In summer, the positive association of precipitation with the EA-CPC/PC3/jet speed is governed by the warm moist westerlies, with the northward displacement of westerlies for a strong jet speed (Figure 9k), combined with the orographic effect accounting for the significant positive correlations in the western Scotland (Figure 7f). Significant positive correlations with the EA are more widespread, with warm moist air being drawn from further south in the central North Atlantic (Figure 9b,k). The cold anomalies over the UK during the positive EA-CPC phase (Figure 9b) may encourage condensation of water vapour in the warm moist Atlantic air, increasing precipitation. SCA-CPC and PC2, have a negative correlation with precipitation along the west of the UK, similar to that in winter (Figure 7b,d). The areas of significance are more extensive in PC2 due to the stronger area of high pressure evident over the North Sea compared with SCA-CPC (Figure 9c,e).

The lack of significant summertime correlation between precipitation and the NAO in north-west Scotland (Figure 7c) is due to the summertime northward shift in the NAO centres of action (Figure 3a,b); for a positive SNAO/PC1, north-west Scotland is just south of the main storm track whereas for a negative phase, it lies just to the north, hence the change in rainfall will not be as great as further south, where in the positive phase the southern UK is well to the south of the storm track, experiencing low rainfall, while in a negative phase, the storm track directs low pressure systems toward this region.

4.5 Drivers of Jet Variability and their relations with UK regional temperature and precipitation patterns.

Table 4 shows correlations between slowly varying drivers of jet stream variability and UK temperature and precipitation. It is unsurprising that many of the jet stream drivers are insignificantly correlated with rainfall or temperature, as any influence is indirect, operating through jet variability. Each driver is only one of several jet predictors, which together explain only a fraction of jet variance. The jet in turn only explains a fraction of precipitation and temperature variance. However, there are some notable significant correlations, particularly in summer. Detrended November sea-ice concentration in the Barents-Kara Sea (BKI) has significant negative correlations with summer rainfall over the whole of the UK with the exception of Northern Scotland, and a significant positive correlation with CET (Table 4b). The sign of the relationships is as expected from the positive association between November sea-ice and summer jet latitude; reduced sea-ice is associated with a southward displacement of the jet in the following summer, with increased rainfall and cooler temperatures. Correlations between November BKI and the summer temperature and rainfall are almost identical over the periods 1955-2014 (0.27 for CET and -0.39 for EWP) and 1979-2016 (0.31; CET and -0.39; EWP), suggesting the relationship is not attributable to recent sea-ice decline.

The positive summer association of precipitation with the AMO, as identified by Sutton and Dong (2012) is significant over northern England, Scotland and Northern Ireland (Table 3b), although not significant further south. The result is consistent with O'Reilly et al. (2017), who identify similar associations between precipitation and the AMO phase, which is dynamical in origin, associated with a cyclonic SLP anomaly over the North Atlantic, leading to increased precipitation over northwestern Europe.

The lagged negative association between summer precipitation and the solar cycle is significant in the south-east of England and eastern Scotland, and England and Wales more generally. While the lag agrees with recent studies (Scaife et al., 2013; Gray et al., 2013; Andrews et al., 2015), these all focus on winter. The lagged solar relationship was not identified as a significant driver of winter jet variability in Hall (2016) and so is not examined here; it is beyond the scope of this paper to test direct associations between a larger number of predictors and UK temperature and precipitation. The significant positive correlation of Scottish precipitation with January tropical Atlantic precipitation (AR; Table 3b) is as-yet unexplained and could be down to chance, although it was identified as a driver of JJA jet speed (Hall et al., 2017b), which has similar positive correlations with Scottish rainfall (Table 2b). It is surprising that correlations in winter are fewer and weaker, whereas predictability of the NAO is greater in winter (e.g. Scaife et al., 2014). This could reflect the increased number of drivers operating in winter, which may mean correlations with individual drivers are weak, or are better represented by factors not included here such as the strength of the stratospheric polar vortex.

5. Discussion

The results presented here demonstrate the limited value of NAO winter seasonal forecasts, when considering UK regional temperature and precipitation variability. The use of forecast of other circulation indices such as the EA, SCA and jet speed and latitude can complement the NAO forecasts, and help to provide a more regional focus. Results agree with van Oldenborgh et al. (2015) who identified that the southern England precipitation anomalies in 2013/14 cannot be attributed to the NAO. Similarly, Wood (2004) reports that although the NAO is a good indicator of winter temperature in the south west of England, there is a less clear association with precipitation, also shown in this study (Figures 4c, 6c). Comas-Bru and McDermott (2014) show similar regional variations in the strength of association between NAO phase and winter precipitation and temperature.

Results presented in this study indicate that in 2013/14, precipitation anomalies in southern England can be attributed to the positive EA phase (Figure 6a) and to the strong jet stream which will itself strengthen the EA (Figure 6f). Returning to Figure 1, only 2014/15 shows a classic NAO distribution of winter precipitation anomalies (see Figure 6c), although the positive rainfall anomalies are not as large as those in 2013/14 and 2015/16. Other winters demonstrating the classic NAO pattern since 2000 are 2001/02, 2004/05, 2011/12 (positive NAO), and 2002/03 and 2009/10 (negative NAO). All other years show patterns that are significantly influenced by other circulation regimes. Similarly, recent summers that show an NAO rainfall anomaly pattern as suggested by Figure 7c are 2004, 2007, 2008, 2012 (all negative NAO). Extending the work to the Atlantic basin, Seierstad et al. (2007) find that the NAO does not explain all the storminess in the Atlantic, with the East Atlantic pattern being a significant factor, particularly where the NAO influence is less strong, explaining the link between the EA and southern England precipitation.

Statistical models have shown good success in predicting the winter NAO (Hall et al., 2017a) and recent work has also begun to identify some possible sources of predictability in the summer jet latitude and speed (Hall et al., 2017b). These influences on the jet stream, and by definition the NAO, are sources of potential predictability of both the winter and summer North Atlantic atmospheric circulation and UK regional temperature and rainfall anomalies. The weak correlations between a number of these influences and UK rainfall and temperature found here are unsurprising. Each driver is only one contributory factor to NAO variance, and a combination of drivers will only explain around 35% (summer) to 56% (winter) of the NAO variance (Hall et al., 2017b, Hall, 2016). Likewise the NAO will only "explain" a limited portion of the rainfall or temperature variance. Any causality is one step removed, meaning correlations between NAO drivers and rainfall and temperature are likely to be lower than correlations between the driver and NAO itself. However, there are promising correlations between a number of drivers of summer jet stream variability, particularly November BKI, the AMO and a lagged solar influence, and UK summer rainfall and temperature. The mechanism for a summer lagged solar effect is unclear, as recent studies identify an association in winter, with a suggested coupling between ocean and atmosphere (Scaife et al., 2013; Gray et al., 2013). This involves storage of heat in the ocean from winter below the shallow summer thermocline, which re-emerges as the latter breaks down in the following winter. However, in Andrews et al. (2015) these positive temperature anomalies are shown persisting in the summer mixed layer of the ocean for up to four years (their figure 4b). The sea-ice association has also to be explained and may depend on persistence of SST anomalies induced by the previous season's ice anomaly. This is an area for future research, together with examining associations with a wider range of drivers than used here, such as the stratospheric polar vortex in winter. It may be possible to use these slowly varying boundary conditions to make direct forecasts of UK seasonal weather.

Developing effective statistical models for the EA-CPC/PC2 and SCA-CPC/PC3 and jet speed will identify further potential sources of seasonal predictability for these indices, which in turn will allow more accurate regional seasonal forecasts of temperature and precipitation to be issued, for both summer and winter. Such models may in turn inform the next generation of dynamical weather forecasting models. Forecasts could also be extended from meteorological variables to more specific metrics used by the power generation industries. For example, high electricity demand in winter is driven by cold conditions, frequently associated with high pressure and anomalous easterly winds prevalent under a negative NAO or SCA-CPC/PC3 pattern. Thornton et al. (2017) find that peak demand is associated with a SCA-CPC/PC3 type circulation, while the wind capacity for electricity generation actually increases slightly under these conditions, compared with when high pressure and low wind speeds are situated directly over the UK. Therefore SCA-CPC/PC3 forecasts could also be associated with wind capacity metrics and would be useful for the wind power industry. Similarly, solar energy generation from photovoltaic (PV) cells is dependent on sunshine duration and cloud cover, which can also be related to the phase of the NAO on a regional basis, (e.g. Colantuano et al., 2014) and may also be associated with other circulation regimes in different parts of the UK. However, a cautionary note should be sounded. Non-stationarities are evident in the NAO and other circulation patterns, due to shifts in centres of action, changes in frequency of occurrence of particular patterns and changes in the preferred phase of the patterns (Hertig et al., 2015). Such non-stationarities are likely to result in changes in the strength of association over time between the circulation patterns and meteorological variables, which will have an impact on regional climate predictability. This study also demonstrates that a station-based NAO is not well-correlated with summertime UK temperature and precipitation, due to shifts in the NAO centres of action during the summer, away from the traditional station locations. Therefore summer seasonal forecasts should focus on jet speed and latitude, or PC-based circulation indices.

6. Summary

These results demonstrate that UK-wide regional variations in temperature and precipitation anomalies are not adequately explained by the NAO alone. The NAO is primarily an indicator of jet latitude variability, here described by a range of indices (NAO-CPC, Hstat, PC1, and in summer, SNAO). In summer, the NAO is positively (negatively) correlated with temperature (precipitation) over the whole of the UK with the exception of northwest Scotland. In northwest Scotland, however, rainfall is most strongly correlated in summer with jet speed and negatively correlated with PC2/SCA-CPC. In winter, while temperatures are significantly positively correlated with the NAO over the whole of the UK, precipitation predictability based on the NAO only applies to northwest of Scotland and England (significant positive correlation), and the east coasts of Scotland and England, where the correlation is negative. Significant correlations for the rest of the UK come from other atmospheric circulation indices: most notably PC2, PC3 and jet speed. Therefore, developing seasonal forecasts for a range of North Atlantic atmospheric circulation metrics would be advantageous for providing improved regional seasonal forecasts of precipitation and temperature, although the NAO is the most effective index in terms of predicting UK temperature anomalies. Seasonal forecasts could be extended to include other meteorological variables and related metrics such as those used by the energy industries.

Acknowledgements

We thank ECMWF, NOAA/OAR/ESRL PSD for providing the ERA-I, 20CRv2c and NCEP/NCAR reanalyses and CPC time series and the Met Office for providing UKCP09, HadUKP and CET, We acknowledge useful discussions with Adam Phillips at UCAR concerning EOFs and the three anonymous reviewers whose helpful comments significantly improved the manuscript.

Supporting Information

Figure S1. UK precipitation regions

Figure S2. Locations of drivers of jet stream variability.

Figure S3. Winter EOFs of SLP, 1980-2014 from 20CR and ERA-I

Figure S4. Summer EOFs of SLP, 1979-2014 from 20CR and ERA-I

References

Adler RF, Huffmann GJ, Chang A, Ferraro R, Xie P, Janowiak J, Rudolf B, Schneider S, Curtis S, Bolvin D, Gruber A, Susskind J, Arkin P. 2003. The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis 1979-present. *Journal of Hydrometeorology* **4**: 1147-1167.

Alexander LV, Jones PD. 2001. Updated precipitation series for the U.K. and discussion of recent extremes. *Atmospheric Science Letters* **1**: 142-150. doi: 10.1006/asle.2001.0025.

Andrews MB, Knight JR, Gray LJ. 2015. A simulated lagged response of the North Atlantic Oscillation to the solar cycle over the period 1960-2009. *Environmental Research Letters* **10**: 054022. doi: 10.1088/1748-9326/10/5/054022.

Barnston AG, Livezey RE. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review* **115**:1083-1126.

Bell VA, Davies HN, Kay AL, Brookshaw A, Scaife AA. 2017. A national-scale seasonal hydrological forecast system: development and evaluation over Britain. *Hydrological and Earth System Sciences Discussions* doi: 10.5194/hess-2017-154.

Benjamini Y, Hochberg Y. 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society* **B57**: 289-300.

Blackburn M, Methven J, Roberts N. 2008. Large-scale context for the UK floods in summer 2007. *Weather* **63(9)**: 280-288, DOI:10.1002/wea.322.

Blanchard-Wrigglesworth E, Armour KC, Bitz CM. 2011. Persistence and inherent predictability of Arctic sea ice in a GCM ensemble and observations. *Journal of Climate* **24**:

231-250, DOI: 10.1175/2010JCLI3775.1.

Brayshaw DJ, Hoskins B, Blackburn M. 2009. The basic ingredients of the North Atlantic storm track. Part I: land-sea contrast and orography, *Journal of the Atmospheric Sciences* **66**: 2539-2558.

Burningham H, French J. 2013. Is the NAO winter index a reliable proxy for wind climate and storminess in northwest Europe? *International Journal of Climatology* **33**: 2036-2049. doi: 10.1002/joc.3571.

Clark RT, Bett PE, Thornton HE, Scaife AA. 2017. Skilful seasonal predictions for the European energy industry. *Environmental Research Letters* **12**: 024002. doi: 10.1088/1748-9326/aa57ab.

Colantuano G, Wang Y, Hanna E, Erdélyi R. 2014. Signature of the North Atlantic Oscillation on British solar radiation availability and PV potential: the winter zonal seesaw. *Solar Energy* 107: 210-219. doi: 10.1016/j.solener.2014.05.045.

Comas-Bru L, McDermott F. 2014. Impact of the EA and SCA patterns on the European twentieth century NAO-winter climate relationship. *Quarterly Journal of the Royal Meteorological Society* **140**: 354-363. doi: 10.1002/qj.2158.

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason Jr BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ. 2011. The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society* **137**: 1-28, DOI: 10.1002/qj.776.

Cropper T, Hanna E, Valente MA, Jónsson T. 2015. A daily Azores-Iceland North Atlantic

Oscillation index back to 1850. *Geoscience Data Journal* **2(1)**: 12-24, DOI: 10.1002/gdj3.23

Czaja A, Marshall J. 2001. Observations of atmosphere-ocean coupling in the North Atlantic. *Quarterly Journal of the Royal Meteorological Society* **127**: 1893-1916.

Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Hólm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette J-J, Park B-k, Peubey C, de Rosnay P, Tavolato C, Thépaut J-N, Vitart F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**: 553-597, DOI: 10.1002/qj.828

Dong B, Sutton RT, Woollings T, Hodges K. 2013a. Variability of the North Atlantic summer storm track: mechanisms and impacts on European climate. *Environmental Research Letters* **8**: 034037. doi: 10.1088/1748-9326/8/3/034037.

Dong B, Sutton RT, Woollings T. 2013b. The extreme European summer 2012. (In "Explaining extreme events of 2012 from a climate perspective"). *Bulletin of the American Meteorological Society* **94(9)**: S28-S32.

Duchon CE. 1979. Lanczos filtering in one and two dimensions. *Journal of Applied Meteorology* **18**: 1016-1022.

Dunstone N, Smith D, Scaife A, Hermanson L, Eade R, Robinson N, Andrews M, Knight J. 2016. Skilful predictions of the winter North Atlantic Oscillation one year ahead. *Nature Geoscience* **9**: 809-814. doi: 10.1038/NGEO2824

Ely CR, Brayshaw DJ, Methven J, Cox J, Pearce O. 2013. Implications of the North Atlantic Oscillation for a UK-Norway renewable power system. *Energy Policy* **62**: 1420-1427. doi: 10.1016/j.enpol.2013.06.037.

Enfield DB, Mestas-Nuñez AM, Trimble PJ. 2001. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophysical Research Letters* **28(10)**: 2077-2080

Feldstein S. 2000. The timescale, power spectra, and climate noise properties of teleconnection patterns. *Journal of Climate* **13**: 4430-4440.

Folland CK, Knight J, Linderholm HW, Fereday D, Ineson S, Hurrell JW. 2009. The Summer North Atlantic Oscillation: past, present and future. *Journal of Climate* **22**: 1082- 1103, doi: 10.1175/2008JCLI2459.1

Folland CK, Scaife AA, Lindesay J, Stephenson DB. 2012. How predictable is northern European winter climate a season ahead? *International Journal of Climatology* **32**: 801-818, doi: 10.1002/joc.2314.

Gray LJ, Scaife AA, Mitchell DM, Osprey S, Ineson S, Hardiman S, Butchart N, Knight J, Sutton R, Kodera K. 2013. A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns. *Journal of Geophysical Research: Atmospheres* **118**: 13 405-13-420, doi: 10.1002/2013JD020062.

Hall R, Erdélyi R, Hanna E, Jones JM, Scaife AA. 2015. Drivers of North Atlantic polar front jet stream variability. *International Journal of Climatology* **35**: 1697-1720. doi: 10.1002/joc.4121.

Hall RJ, 2016. The North Atlantic polar front jet stream: variability and predictability, 1871-2014. *Unpublished PhD thesis, University of Sheffield.*

Hall RJ, Scaife AA, Hanna E, Jones JM, Erdélyi R. 2017a. Simple statistical probabilistic forecasts of the winter NAO. *Weather and Forecasting* **32**: 1585-1601. doi: 10.1175/WAF-D-16-0124.S1.

Hall RJ, Jones JM, Hanna E, Scaife AA, Erdélyi R. 2017b. Drivers and potential predictability of summer North Atlantic polar front jet variability. *Climate Dynamics* **48**: 3869-3887. doi: 10.1007/s00382-016-3307-0

Hanna E, Cropper TE. 2017. North Atlantic Oscillation. *Oxford Research Encyclopedia of Climate Science.* doi: 10.1093/acrefore/9780190228620.013.22

Hertig E, Beck C, Wanner H, Jacobeit J. 2015. A review of non-stationarities in climate variability of the last century with a focus on the North Atlantic-European sector. *Earth Science Reviews* **147**: 1-17. doi: 10.1016/j.earscirev.2015.04.009.

Hulme M, Barrow E, (eds). 1997. *Climates of the British Isles: present, past and future.* Routledge, London.

Huntingford C, Marsh T, Scaife AA, Kendon EJ, Hannaford J, Kay AL, Lockwood M, Prudhomme C, Reynard NS, Parry S, Lowe JA, Screen JA, Ward HC, Roberts M, Stott PA, Bell VA, Bailey M, Jenkins A, Legg T, Otto FEL, Massey N, Schaller N, Slingo J, Allen MR. 2014. Potential influences on the United Kingdom's floods of winter 2013/14. *Nature Climate Change* **4**: 769-777. doi: 10.1038/NCLIMATE2314.

Hurrell JW. 1995. Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science* **269**: 676-679.

Hurrell JW, Kushnir Y, Visbeck M, Ottersen G. 2003. An overview odf the North Atlantic

Oscillation. In Hurrell JW, Kushnir Y, Ottersen G, Visbeck M, (eds). *The North Atlantic Oscllation, Climatic Significance and Environmental Impact.* AGU Geophysical Monograph 134, pp1-35.

Hurrell JW, Deser C. 2009. North Atlantic climate variability: the role of the North Atlantic Oscillation. *Journal of Marine Systems* **78**: 228-41. doi: 10.1016/j.jmarsys.2008.11.026.

James IN, James PM. 1989. Ultra-low-frequency variability in a simple atmospheric circulation mode. *Nature* **342**: 53-55.

Jones PD, Jónsson T, Wheeler D. 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *International Journal of Climatology* **17**: 1433-1450.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deavon D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437-471.

Kaplan A, Cane M, Kushnir Y, Clement A, Blumenthal M, Rajagopalan B. 1998. Analyses of global sea surface temperature 1856-1991, *Journal of Geophysical Research* **103**: 18567-18589.

Lim YK. 2015. The East Atlantic / West Russia teleconnection in the North Atlantic: climate impact and relation to Rossby wave propagation. *Climate Dynamics* **44**: 3211-3222. doi: 10.1007/s00382-014-2381-4.

Manley G. 1953. The mean temperature of Central England, 1698-1952. *Quarterly journal of the Royal Meteorological Society* **79**: 242-261.

Moore GWK, Renfrew IA. 2012. Cold European winters: interplay between the NAO and the East Atlantic mode. *Atmospheric Science Letters* **13**: 1-8. doi: 10.1002/asl.356.

Naujokat B. 1986. An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *Journal of the Atmospheric Sciences* **43**: 1873-1877.

North GR, Bell TL, Cahalan RF, Moenig FJ. 1982. Sampling errors in the estimation of empirical orthogonal functions *Monthly Weather Review* **110**: 669–706.

O'Reilly C, Woollings T, Zanna L. 2017. The dynamical influence of the Atlantic Multidecadal Oscillation on continental climate. *Journal of Climate*. doi: 10.1175/JCLI-D-16-0345.1, in press.

Palin EJ, Scaife AA, Wallace E, Pope ECD, Arribas A, Brookshaw A. 2016. Skillful seasonal forecasts of winter disruption to the U.K. transport system. *Journal of Applied Meteorology and Climatology* 55: 325-344. doi: 10.1175/JAMC-D-15-0102.1.

Parker DE, Legg TP, Folland CK. 2003. A new daily central England temperature series, 1772-1991. *International Journal of Climatology* **12**: 317-342.

Perry M, Hollis D. 2005. The development of a new set of long-term climate averages for the UK. *International Journal of Climatology* **25**: 1023-1039. doi: 10.1002/joc.1160.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres* **108**(D14): 4407. doi: 10.1029/2002JD002670.

Robinson DA, Estilow TW, NOAA CDR program 2012. Accessed 5th March 2017. NOAA Climate Data Record (CDR) of Northern Hemisphere (NH) Snowcover extent (SCE), v01r01. NOAA National Climatic Data Center. doi: 10.7289/V5N014G9.

Scaife AA, Ineson S, Knight JR, Gray L, Kodera K, Smith DM. 2013. A mechanism for lagged North Atlantic climate response to solar variability. *Geophysical Research Letters* **40(2)**: 434-439. doi: 10.1002/grl.50099.

Scaife AA, Arribas A, Blockley E, Brookshaw A, Clark RT, Dunstone N, Eade R, Fereday D, Folland CK, Gordon M, Hermanson L, Knight JR, Lea DJ, MacLachlan C, Maidens A, Martin M, Peterson AK, Smith D, Vellinga M, Wallace E, Waters J, Williams A. 2014a. Skillful long-range prediction of European and North American winters. *Geophysical Research Letters* **41**: 2514-2519. doi: 10.1002/2014GL059637.

Seierstad IA, Stephenson DB, Kvamstø NG. 2007. How useful are teleconnection patterns for explaining variability in extratropical storminess? *Tellus* **59A**: 170-181. doi: 10.1111/j.1600-0870.2007.00226.x.

Smith DM, Scaife AA, Eade R, Knight JR. 2016. Seasonal to decadal prediction of the winter North Atlantic Oscillation: emerging capability and future prospects. *Quarterly Journal of the Royal Meteorological Society* **142**: 611-617. doi: 10.1002/qj.2479.

Stockdale TN, Molteni F, Ferranti L. 2015. Atmospheric initial conditions and the predictability of the Arctic Oscillation. *Geophysical Research Letters* **42**: 1173-1179. doi: 10.1002/2014GL062681.

Sutton RT, Dong B. 2012. Atlantic Ocean influence on a shift in European climate in the 1990s. *Nature Geoscience* **5**: 788-792. doi: 10.1038/ngeo1595.

Svensson C, Brookshaw A, Scaife AA, Bell VA, Mackay JD, Jackson CR, Hannaford J, Davies HN, Arribas A, Stanley S. 2015. Long-range forecasts of UK winter hydrology. *Environmental Research Letters* **10**: 064006. doi: 10.1088/1748-9326/10/6/064006.

Thornton HE, Scaife AA, Hoskins BJ, Brayshaw DJ. 2017. The relationship between wind power, electricity demand and winter weather patterns in Great Britain. *Environmental Research Letters* **12**: 064017. doi: 10.1088/1748-9326/aa69c6.

Vallis GK, Gerber EP. 2008. Local and hemispheric dynamics of the North Atlantic Oscillation, annular patterns and the zonal index. *Dynamics of Oceans and Atmospheres* **44**: 184-212. doi: 10.1016/j.dynatmoce.2007.04.003.

Van Oldenborgh GJ, Stephenson DB, Sterl A, Vautard R, Yiou P, Drijfhout SS, von Storch H, van den Dool H. 2015. Drivers of the 2013/14 winter floods in the UK. *Nature Climate Change* **5**: 490-491.

Wallace JM, Gutzler DS. 1981. Teleconnections in the geopotential height field during the northern hemisphere winter. *Monthly Weather Review* **109**: 784-812.

Wang L, Ting M, Kushner P. 2017. A robust empirical seasonal prediction of winter NAO and surface climate. *Scientific Reports* **7**: 279. doi: 10.1038/s41598-017-00353-y.

Wanner H, Brönnimann S, Casdty C, Gyalistras D, Luterbacher J, Schmutz C, Stephenson DB, Xoplaki E. 2001. North Atlantic Oscillation-concepts and studies. *Surveys in Geophysics* **22**: 321-382.

Wigley TML, Lough JM, Jones PD. 1984. Spatial patterns of precipitation in England and Wales and a revised, homogenous England and Wales precipitation series. *Journal of Climatology* **4**: 1-25.

Wilks DS. 2011. *Statistical Methods for the Atmospheric Sciences,* third edition. Academic Press, New York.

Wood NLH. 2004. Regional climate trends in south-west England and the North Atlantic Oscillation. *Weather* **59**: 39-41. doi: 10.1256/wea.28.03.

Woollings T. 2010. Dynamical influences on European climate: an uncertain future. *Philosophical Transactions of the Royal Society of London A: mathematical, physical and engineering sciences* **368**: 3722-3756. doi: 10.1098/rsta.2010.0040.

Woollings T, Blackburn M. 2012. The North Atlantic jet stream under climate change and its relation to the NAO and EA patterns. *Journal of Climate* **25**: 886-902. doi: 10.1175/JCLI-D-11-00087.1.

Woollings T, Hannachi A, Hoskins B. 2010b. Variability of the North Atlantic eddy-driven jet stream, *Quarterly Journal of the Royal Meteorological Society* **136**: 856-868. doi: 10.1002/qj.625.

Woollings T, Czuchnicki C, Franzke C. 2014. Twentieth century North Atlantic jet variability. *Quarterly Journal of the Royal Meteorological Society* **140**: 783-791. doi: 10.1002/qj.2197.

Zubiate L, McDermott F, Sweeney C, O'Malley M. 2016. Spatial variability in winter NAO-wind relationships in western Europe linked to concomitant states of the East Atlantic and Scandinavian patterns. *Quarterly Journal of the Royal Meteorological Society* **143**: 552-562. doi: 10.1002/qj.2943.

Figure Captions.

Figure 1. Rainfall anomaly maps for winter a) 2013-14, b) 2014-15 and c) 2015-16 relative to 1981-2010 climatology. The Hurrell PC NAO indices for the three winters are 0.59, 1.67 and 0.95 respectively. (CPC indices are: NAO: 0.56, 1.42, 0.99; EA: 0.57, 0.16, 2.00; SCA: 0.71, -0.32, -0.38). Figures from the UK Met Office.

Figure 2. differences between winter 2013/14 and 2014/15 for a) zonal windspeed at 850hPa and b) SLP. Data from NCEP/NCAR reanalysis. Contours are shown for the major tickmarks, with negative contours dotted.

Figure 3. First 3 EOFs of SLP for a) winter and b) summer derived from 20CRv2, 1951-2014. The percentage of SLP variance explained by each EOF is indicated.

Figure 4. Correlations of DJF mean temperature with metrics of Atlantic atmospheric circulation, 1952-2011. Black contours denote correlations significant at p≤0.05. Data from UKCP09 5km gridded data.

Figure 5. As for Figure 4 except for JJA mean temperature, 1951-2011.

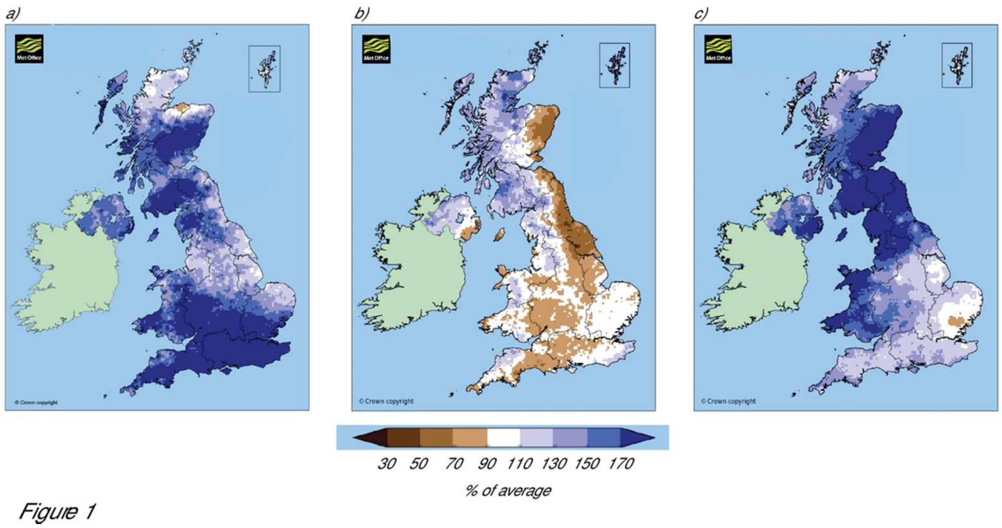
Figure 6. As for Figure 4 except for DJF total precipitation, 1952-2011. Note that blue shows a positive correlation.

Figure 7. As for Figure 4, except for JJA total precipitation, 1951-2011. Note that blue shows a positive correlation.

Figure 8. Composites of 850hPa vector wind and 925hPa air temperature anomalies, for each of the DJF circulation indices. Figures derived from composites of the ten highest

minus the 10 lowest years of the index in question, from 1951-2014. Taken from NCEP/NCAR reanalysis.

Figure 9. As for Figure 8, except for JJA.



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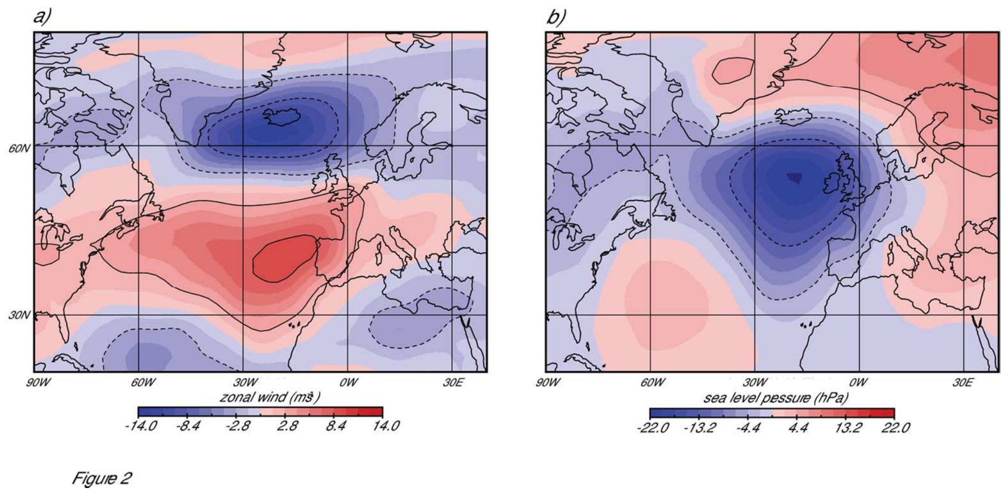

Figure 2. differences between winter 2013/14 and 2014/15 for a) zonal windspeed at 850hPa and b) SLP. Data from NCEP/NCAR reanalysis. Contours are shown for the major tickmarks, with negative contours dotted.

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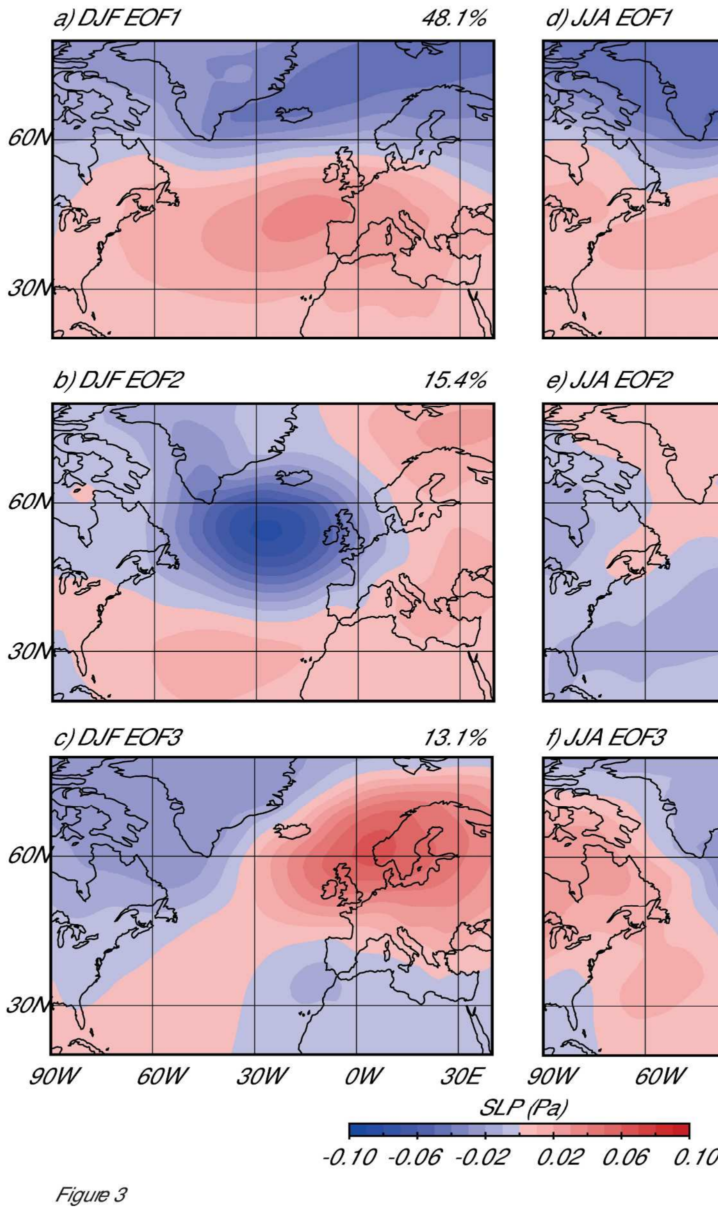

Figure 3. First 3 EOFs of SLP for a) winter and b) summer derived from 20CRv2, 1951-2014. The percentage of SLP variance explained by each EOF is indicated.

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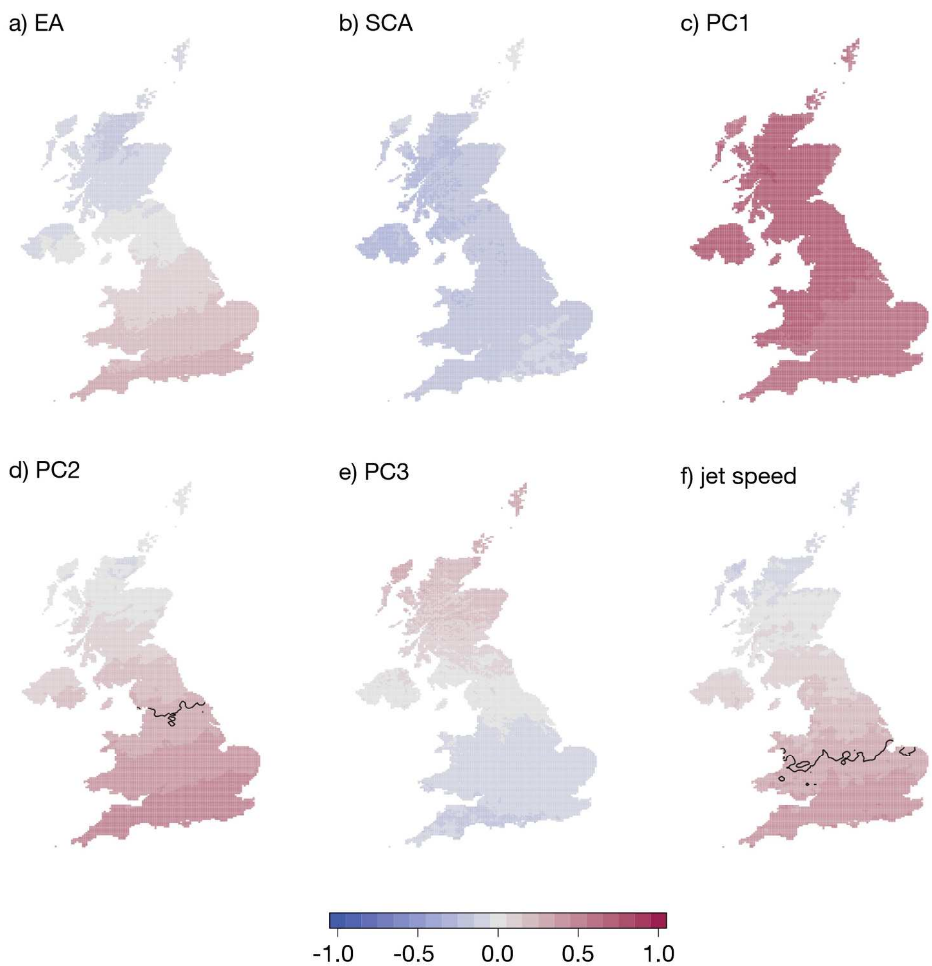

Figure 4

Figure 4. Correlations of DJF mean temperature with metrics of Atlantic atmospheric circulation, 1952-2011. Black contours denote correlations significant at p≤0.05. Data from UKCP09 5km gridded data.

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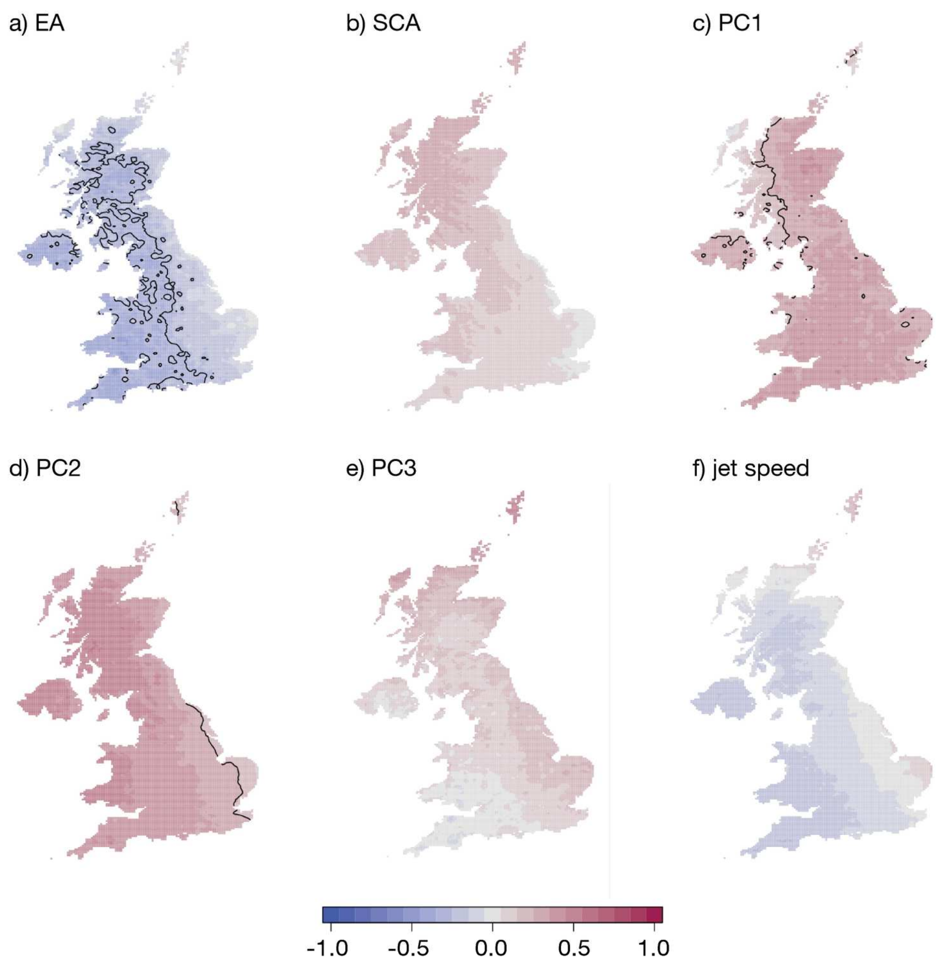

Figure 5

Figure 5. As for Figure 4 except for JJA mean temperature, 1951-2011.

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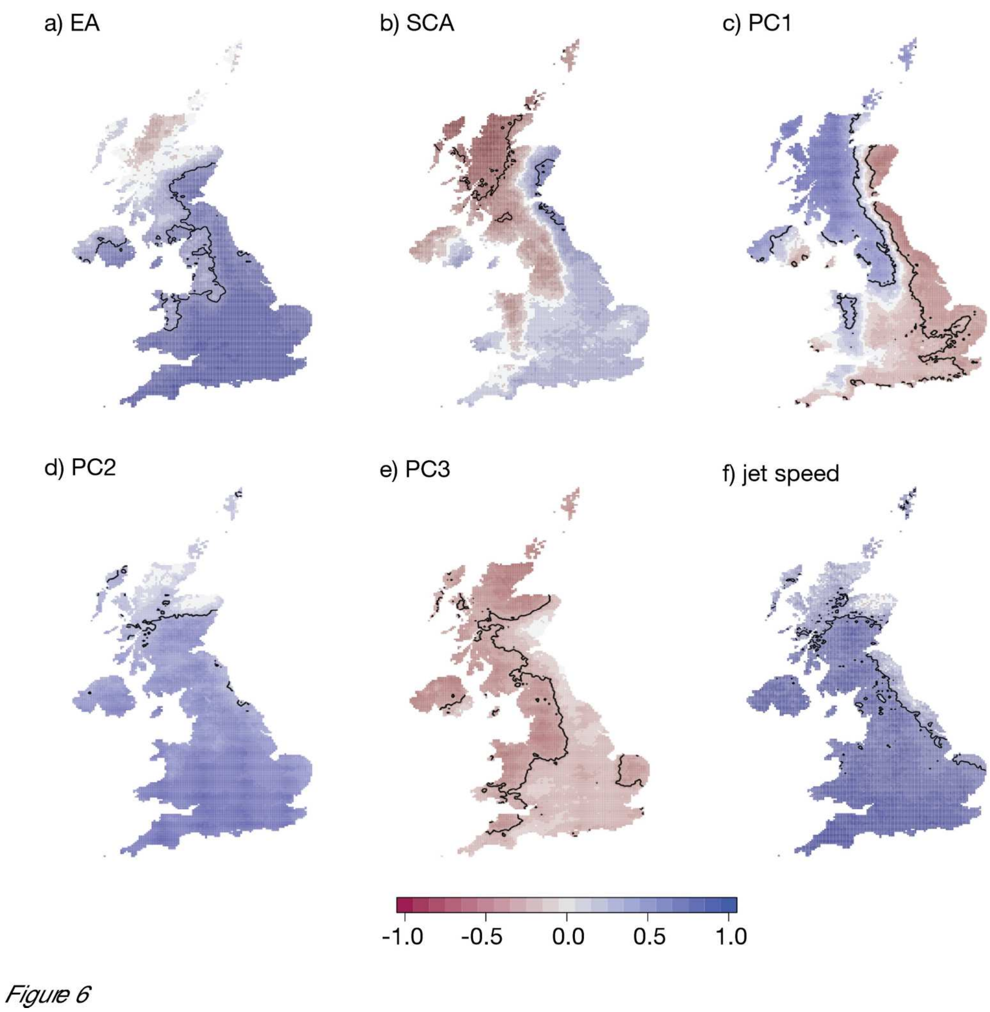

Figure 6. As for Figure 4 except for DJF total precipitation, 1952-2011. Note that blue shows a positive correlation.

177x176mm (300 x 300 DPI)

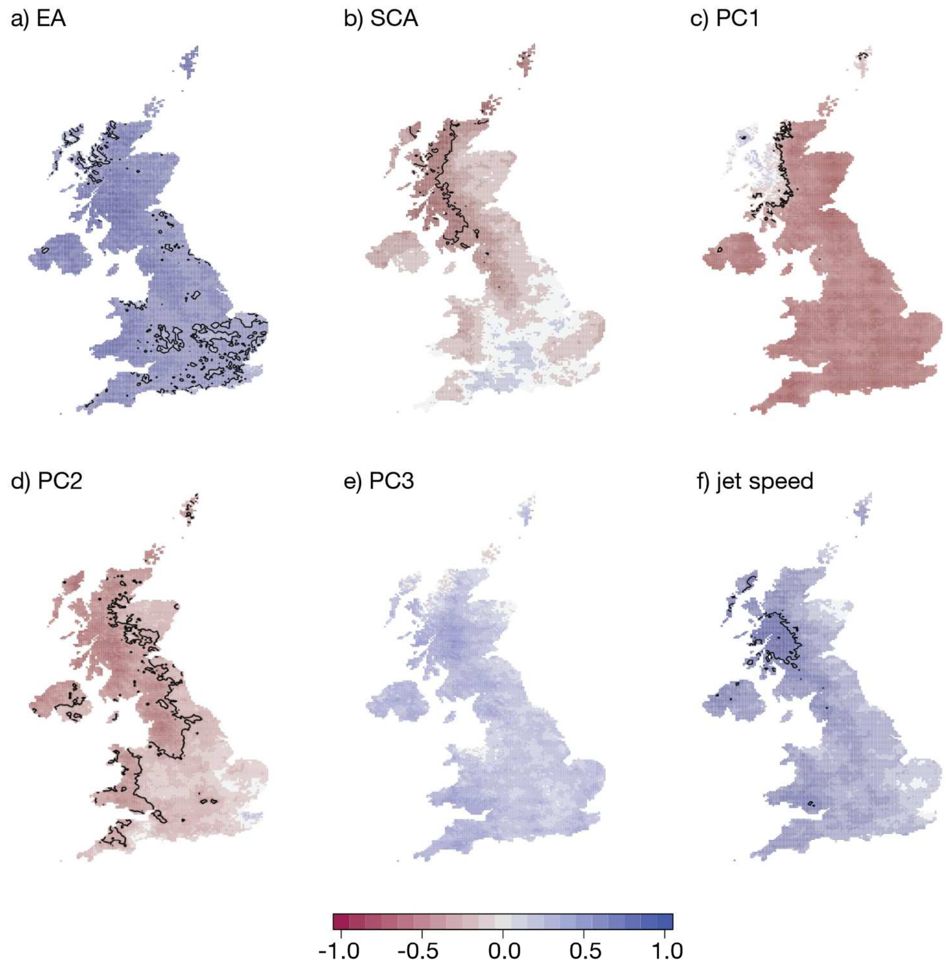

Figure 7

Figure 7. As for Figure 4, except for JJA total precipitation, 1951-2011. Note that blue shows a positive correlation.

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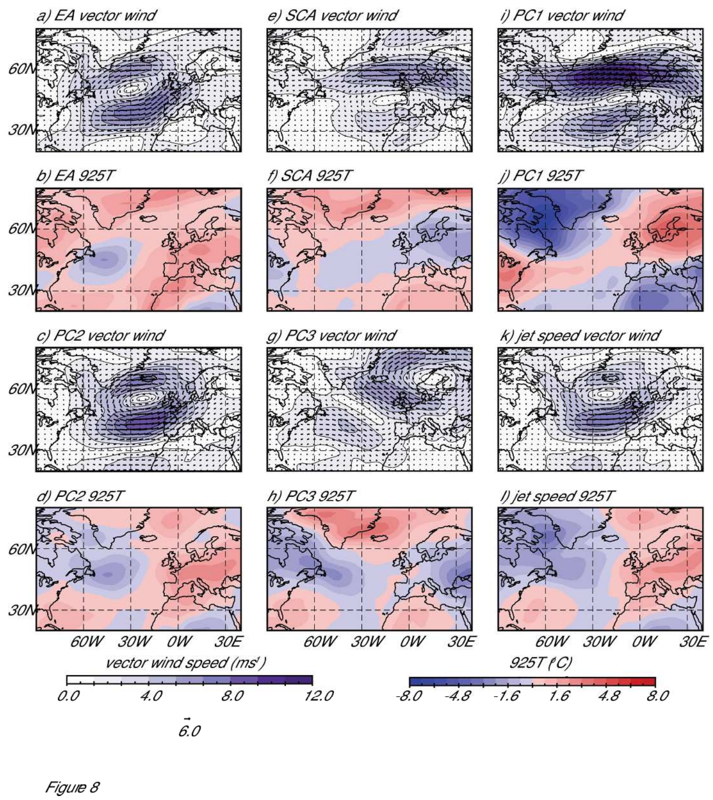


Figure 8. Composites of 850hPa vector wind and 925hPa air temperature anomalies, for each of the DJF circulation indices. Figures derived from composites of the ten highest minus the 10 lowest years of the index in question, from 1951-2014. Taken from NCEP/NCAR reanalysis.

222x175mm (300 x 300 DPI)

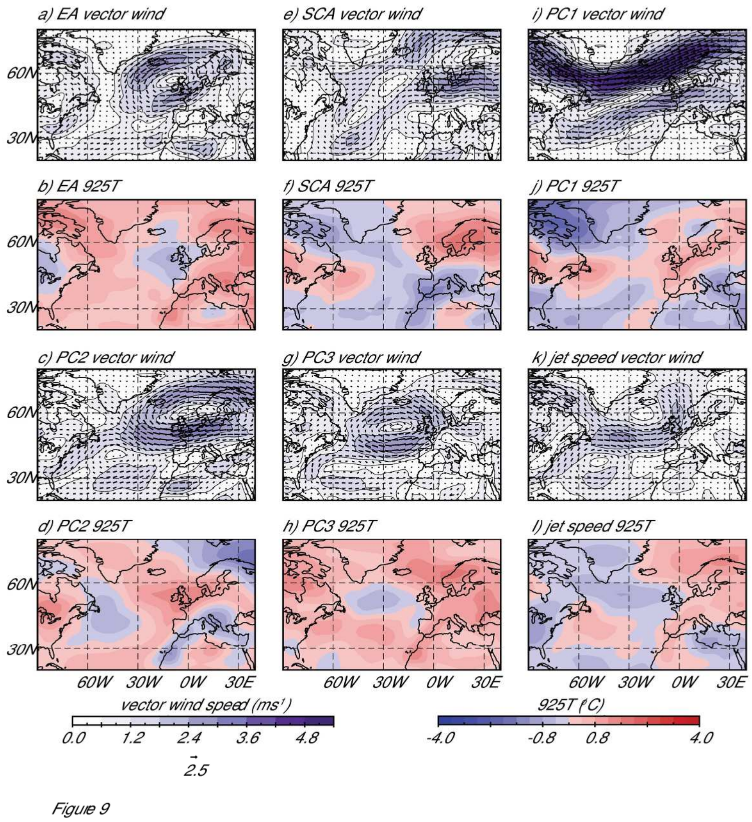


Figure 9. As for Figure 8, except for JJA.

225x191mm (300 x 300 DPI)

dataset	Variable used	Region selected	Dates used
NAO-CPC/EA-CPC/SCA-CPC	500hPha GPH	Northern hemisphere, 20-90N	1951-2016
SNAO	SLP (NCEP/NCAR)	90W-30E, 40-70N	1951-2016
Hurrell station NAO	SLP	90W-40E, 20-80N	1951-2016
CET	seasonal temperature	Central England	1951-2016
HadUKP	Seasonal precipitation	UK regions	1951-2016
UKCP09	temperature, precipitation	5km grid over UK	1951-2011
20CRv2c	zonal wind (jet speed and latitude SLP (EOFs)	60-0W, 16-76N 90W-40E, 20-80N	1951-2014 1951-2014
ERA-I	Zonal wind (jet speed and latitude SLP (EOFs)	60-0W, 16-76N 90W-40E, 20-80N	1979-2016 1979-2016
NCEP-NCAR reanalysis	850hPa Vector winds, 925hpA temperature	90W-40E, 20-80N	1951-2016
HadISST1	Sea ice concentration SST (NA Tripole) N3.4	30-90E,70-85N (BKI) 35-0W, 80-90N (GI) 60-40W, 40-55N minus 80-60W,25-35N 120-170W, 5N-5S	1951-2016 1951-2016 1951-2016
snowcover	Snowcover extent, Rutgers University	55-150E, 45-80N (Eurasia) 130-70W, 40-70N) (N. America)	1979-2016
AMO	Kaplan SST	0-70N (N Atlantic)	1951-2016
Solar variability	Sunspot numbers	NA	1951-2016
QBO	30hPa zonal winds	NA	1951-2016
GPCPv2	Tropical Atlantic precipitation	10-35W, 5N-5S	1979-2016

Table 1. Summary of datasets used, the regions and time periods extracted.

a) DJF	NAO-CPC	EA	SCA	PC1	PC2	PC3	Jet speed	Jet latitude	Hstat
NAO-CPC		-0.17	**-0.30**	**0.89**	0.11	-0.14	**0.28**	**0.77**	**0.94**
EA	-0.15		0.07	-0.20	**0.82**	0.13	**0.53**	**-0.57**	-0.16
SCA	**-0.50**	-0.02		**-0.46**	-0.02	**0.35**	-0.09	**-0.29**	**-0.28**
PC1	**0.90**	-0.21	**-0.67**		0.004	-0.05	0.18	**0.82**	**0.89**
PC2	0.16	**0.82**	-0.19	0.04		-0.00	**0.73**	**-0.38**	0.12
PC3 swap	-0.13	0.08	0.29	-0.05	0.01		0.07	0.07	-0.07
Jet speed	**0.43**	**0.50**	-0.23	0.31	**0.77**	-0.19		-0.07	**0.3**
Jet latitude	**0.71**	**-0.61**	**-0.37**	**0.79**	**-0.42**	-0.03	-0.04		**0.79**
Hstat	**0.92**	-0.10	**-0.49**	**0.89**	0.25	0.02	**0.52**	**0.69**	

b) JJA	NAO-CPC	EA	SCA	PC1	PC2	PC3	SNAO	Jet speed	Jet latitude	Hstat
NAO-CPC		**-0.25**	0.21	**0.90**	0.00	-0.01	**0.81**	0.12	**0.71**	**0.47**
EA	-0.05		-0.24	-0.21	**-0.38**	**0.37**	**-0.44**	**0.36**	**-0.37**	**0.28**
SCA	0.22	-0.22		0.25	**0.43**	0.10	**0.29**	-0.07	0.19	0.02
PC1	**0.90**	-0.04	0.17		-0.04	-0.03	**0.85**	0.10	**0.74**	**0.53**
PC2	0.10	**0.38**	-0.04	0.04		0.07	**0.37**	**-0.53**	0.15	**-0.40**
PC3	0.26	0.33	0.25	0.22	-0.10		**0.30**	**0.59**	-0.24	**0.28**
SNAO	**0.80**	**-0.34**	0.25	**0.87**	-0.24	-0.09		-0.24	**0.76**	**0.27**
Jet speed	0.32	**0.45**	-0.05	0.27	**0.56**	**0.51**	-0.06		-0.13	**0.50**
Jet latitude	**0.64**	-0.30	0.09	**0.68**	0.33	-0.13	**0.73**	-0.09		**0.37**
Hstat	**0.56**	0.29	0.11	**0.56**	**0.43**	0.06	**0.40**	**0.50**	**0.40**	

Table 2. Table of correlations between North Atlantic atmospheric circulation indices for a) winter (DJF) and b) summer (JJA). Bold denotes correlation coefficients significant at p≤0.05.

Black figures above the diagonal denote correlations over 1951-2014, based on 20CRv2c SLP data for the PCs, while red figures are over the period 1979-2016 (JJA) and 1980-2016 (DJF), based on ERA-I SLP data for the PCs. NB for JJA, 1979+, PC2 is closer to EA and PC3 to SCA, whereas for 1950 this is reversed, explaining discrepancies in correlations (highlighted).

a) DJF	CET	EW	SEE	SWE	CE	NWE	NEE	S	SS	NS	ES	NI
NAO-CPC	0.63	0.09	-0.07	0.19	-0.14	0.48	-0.08	0.69	0.71	0.77	0.20	0.41
EA	0.16	0.63	0.60	0.64	0.6	0.34	0.60	0.24	0.24	0.09	0.37	0.31
SCA	-0.19	0.10	0.22	0.07	0.17	-0.25	0.18	-0.29	-0.29	-0.41	0.02	-0.11
lat	0.42	-0.37	-0.49	-0.30	-0.49	0.10	-0.48	0.32	0.35	0.50	-0.15	0.08
speed	0.33	0.63	0.59	0.70	0.47	0.52	0.44	0.51	0.54	0.37	0.47	0.57
PC1	0.67	-0.14	-0.29	-0.04	-0.34	0.35	-0.29	0.60	0.64	0.76	0.02	0.25
PC2	0.41	0.76	0.73	0.80	0.63	0.57	0.60	0.49	0.48	0.35	0.48	0.52
PC3	-0.09	-0.29	-0.22	-0.25	-0.24	-0.47	-0.19	-0.40	-0.35	-0.34	-0.40	-0.49
Hstat	0.65	0.06	-0.08	0.16	-0.15	0.44	-0.14	0.64	0.67	0.75	0.14	0.38

b)JJA	CET	EW	SEE	SWE	CE	NWE	NEE	S	SS	NS	ES	NI
NAO-CPC	0.44	-0.65	-0.59	-0.6	-0.58	-0.61	-0.63	-0.52	-0.51	-0.17	-0.60	-0.59
EA	-0.33	0.40	0.31	0.41	0.34	0.45	0.35	0.50	0.51	0.44	0.39	0.47
SCA	0.14	-0.09	-0.05	-0.05	-0.03	-0.25	-0.10	-0.30	-0.35	-0.41	-0.12	-0.20
lat	0.35	-0.72	-0.67	-0.68	-0.68	-0.60	-0.67	-0.57	-0.54	-0.23	-0.63	-0.70
speed	-0.12	0.24	0.16	0.29	0.18	0.25	0.20	0.36	0.41	0.46	0.16	0.30
PC1	0.47	-0.67	-0.64	-0.62	-0.60	-0.58	-0.63	-0.57	-0.54	-0.23	-0.63	-0.70
PC2	0.41	-0.26	-0.15	-0.27	-0.14	-0.44	-0.26	-0.47	-0.52	-0.62	-0.24	-0.38
PC3	0.09	0.26	0.19	0.36	0.21	0.19	0.19	0.28	0.32	0.26	0.19	0.29
Hstat	0.02	-0.25	-0.30	-0.15	-0.30	-0.13	-0.23	-0.05	0.00	0.28	-0.26	-0.14
SNAO	0.56	-0.80	-0.71	-0.77	-0.69	-0.78	-0.76	-0.77	-0.76	-0.44	-0.77	-0.82

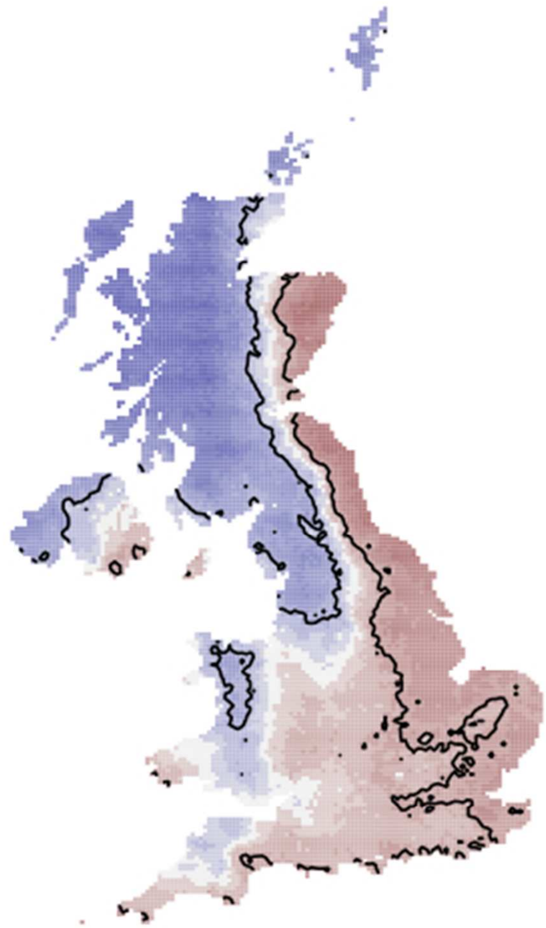
Table 3. Correlations between detrended atmospheric circulation indices and detrended time series of temperature and precipitation for UK regions, 1951-2014 for a) winter (DJF) and b) summer (JJA). Dark (light) blue shows negative correlation significant at p≤0.01 (0.05). Dark (light) orange shows positive correlation significant at p ≤0.01 (0.05). CET = Central England temperature. Precipitation regions are: EW: England and Wales, SEE: South-east England, SWE: south-west England, CEP: central England, NWE: north west England, NEE; north east England, S: Scotland, SS: southern Scotland, NS: Northern Scotland, ES: East Scotland, NI: Northern Ireland.

a) DJF Jet driver	CET	EW	SEE	SWE	CE	NWE	NEE	S	SS	NS	ES	NI
November BKI	0.36	0.06	-0.05	0.11	0.08	0.16	0	0.2	0.21	0.23	0.04	0.21
September GI	0.15	0.14	0.21	0.15	0.1	0.07	-0.01	0.06	0.09	0	0.1	0.11
October Eu snow*	-0.17	0.25	0.35	0.21	0.32	-0.03	0.22	-0.19	-0.17	-0.32	0.11	0.04
September AMO	-0.04	0.02	0.04	-0.03	0.07	0.02	0.05	-0.03	-0.05	-0.07	0.08	-0.01
June SST tripole	0.12	0.1	0.04	0.14	0.06	0.11	0.06	0.13	0.08	0.15	0.14	0.13
October QBO	0.06	-0.01	-0.03	-0.03	-0.05	0.09	0.02	0.16	0.13	0.16	0.15	0.04
October N3.4	-0.16	0.13	0.22	0.11	0.2	-0.12	0.1	-0.23	-0.23	-0.26	-0.09	-0.14

b) JJA jet driver	CET	EW	SEE	SWE	CE	NWE	NEE	S	SS	NS	ES	NI
November BKI	0.27	-0.39	-0.3	-0.35	-0.37	-0.41	-0.42	-0.43	-0.39	-0.24	-0.46	-0.47
February NA snow*	-0.21	0.25	0.15	0.23	0.26	0.23	0.31	0.27	0.25	0.17	0.32	0.26
January AMO	0.01	0.26	0.17	0.17	0.26	0.31	0.36	0.29	0.24	0.08	0.37	0.27
May SST tripole	-0.05	-0.03	0.01	-0.07	0.04	-0.06	-0.06	-0.19	-0.16	-0.25	-0.14	-0.05
June solar lead 4	0.14	-0.26	-0.32	-0.25	-0.17	-0.25	-0.21	-0.23	-0.24	-0.05	-0.27	-0.21
January AR*	-0.15	0.15	0.1	0.14	0.08	0.19	0.19	0.33	0.35	0.33	0.25	0.19

Table 4. Correlations between identified detrended drivers of jet speed and latitude for a) winter (DJF) and b) summer (JJA) with precipitation and temperature (CET) time series for the UK, 1955-2014, except for those marked * where the correlation is from 1980 due to availability of predictor time series. Significant correlations are orange (positive) and blue (negative) with p≤ 0.05 (0.01) light (dark). BKI =Barents-Kara sea-ice, GI=Greenland Sea ice, Eu snow=Eurasian snow cover, NA snow=North American snow cover, AMO =Atlantic

Multidecadal Oscillation, tripole SST =North Atlantic tripole pattern of SST, QBO=Quasi-Biennial Oscillation, solar lead 4=solar sunspot cycle leading by four years, AR=tropical Atlantic rainfall. UK regions are as in Figure S1.



North Atlantic circulation indices: links with summer and winter UK temperature and precipitation and implications for seasonal forecasting.

Richard J. Hall* and Edward Hanna

The winter North Atlantic Oscillation is predictable from a few months ahead, but does not explain all regional UK precipitation and temperature anomalies. We examine associations between a number of circulation indices and UK summer and winter temperature and rainfall patterns. The East Atlantic and Scandinavian patterns explain significant regional variations in UK weather, and some drivers of summer jet stream variability are directly associated with summer temperature and precipitation variability. There is potential to develop improved regional seasonal forecasts.